Exhibit A

Improvement of Optical NRZ- and RZ-Duobinary Transmission Systems With Narrow Bandwidth Optical Filters

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***Abstract*—We show that a narrow bandwidth optical filter at the receiver side can greatly improve the receiver sensitivity of a nonreturn-to-zero (NRZ)-duobinary system. We propose to use the narrow bandwidth filtering at the receiver side of a return-to-zero (RZ)-duobinary system to convert RZ-duobinary to NRZ-duobinary, so that the system tolerance to residual chromatic dispersion can be increased while its resistance to nonlinearity in transmission is still maintained. The idea is demonstrated with experiments.**

***Index Terms*—Chromatic dispersion, duobinary, filters, modulation formats, optical fiber communications.**

I. Introduction

Optical duobinary modulation has attracted much attention due to its compact spectrum and good transmission performance [1]–[10]. It has been shown that nonreturn-to-zero (NRZ) duobinary format can tolerate about three times more chromatic dispersion than ordinary NRZ [2]–[5], and that return-to-zero (RZ)-duobinary is more tolerant to nonlinearity than ordinary RZ in highly dispersed pseudolinear transmission systems [11].

Large dispersion tolerance of duobinary transmission mainly comes from the bandwidth limiting filter in the transmitter [3], [4]. However, because of such filters, the back-to-back sensitivity of NRZ-duobinary is reduced and typically about 2 dB worse than NRZ if an ordinary intensity-modulation direct-detection receiver is used. Many approaches to increase the back-to-back sensitivity of NRZ-duobinary has been proposed and demonstrated, such as transmitter side techniques [6]–[8] and over-sampling technique at the receiver side [9]. Numerical simulation found that the optimum receiver filter bandwidth of NRZ-duobinary were very different from those of ordinary NRZ [10].

In this letter, we first demonstrate that a narrow bandwidth optical filter at the receiver can significantly improve the sensitivity of an NRZ-duobinary system. Then we show that by using the narrow bandwidth filtering to convert RZ-duobinary to NRZ-duobinary at the receiver side, the chromatic dispersion tolerance of an RZ-duobinary system can be greatly increased.

II. Experimental Results and Discussions

Fig. 1 shows the schematic of the experimental setup. A commercially available duobinary transmitter with a 2.5-GHz duobinary electrical filter generated a 9.953-Gb/s NRZ-duobinary signal. A pulse carver was positioned after the duobinary transmitter to produce a 33% duty-cycle RZ-duobinary. Different lengths of fibers induced the required chromatic dispersion. The launch power into the fiber was kept low (less than -5 dBm) to avoid nonlinear transmission. By adjusting the signal power entering erbium-doped fiber amplifier (EDFA1) with an attenuator, we could change the optical signal-to-noise ratio (OSNR) at the input of the receiver. The optical tunable filter is a free space grating-based filter with adjustable center frequency and filter bandwidth [12], which has the intensity response close to second-order super-Gaussian filter and a negligible chirp in its passband. Since the next-generation optical networks are expected to run with forward error correction (FEC) coding, the system performance was measured at bit-error rate (BER) $= 10^{-3}$, which can be corrected to 10^{-15} by the enhanced FEC with 7% overhead [13]. Practical systems usually run with BER well below this value considering the margins for various degradations. But the conclusions in this letter do not change if the performance is measured at other BER values.

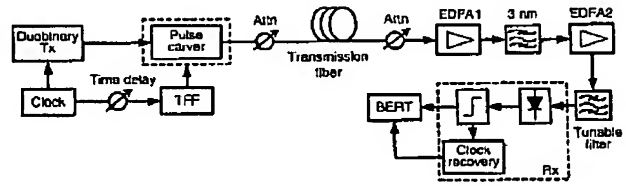

Fig. 1. Schematic diagram of the experimental setup. TFF: toggle flip-flop. Attn: attenuator. Tx: transmitter. Rx: receiver.

First, we measured the required OSNR at BER $= 10^{-3}$ for back-to-back operation of NRZ- and RZ-duobinary systems with different optical filter bandwidths. The result is shown in Fig. 2. The OSNR was measured in 0.1-nm noise bandwidth. It shows that the optimum optical bandwidth for back-to-back NRZ-duobinary is about 10 GHz (one time bit rate), which is smaller than NRZ (about 14 GHz from our measurement). The optimum optical filter bandwidth is about 27 GHz for RZ-duobinary, which is close to that of conventional RZ. Shrinking the optical filter bandwidth can reduce amplified spontaneous emission (ASE) noise in the receiver, so decreasing the filter bandwidth can improve the system sensitivity as long as the filter does not induce significant signal loss and distortions. A visible feature in Fig. 2 is that there is a large improvement (about 2 dB) when the filter bandwidth is reduced from 20 to 10 GHz for NRZ-duobinary, which

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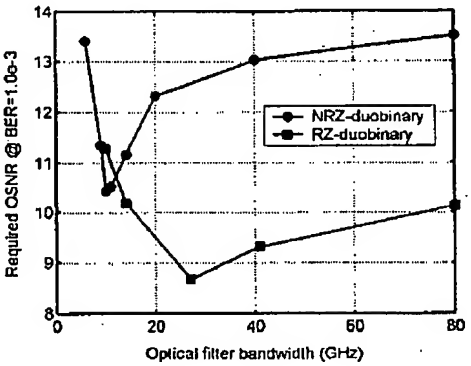

Fig. 2. Required OSNR at BER $= 10^{-3}$ versus optical filter bandwidth for back-to-back NRZ- and RZ-duobinary.

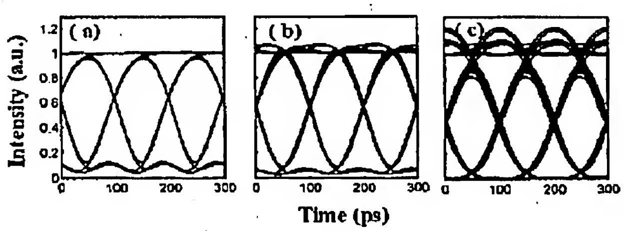

Fig. 3. Simulated eye diagrams of NRZ-duobinary with (a) 20-, (b) 10-, and (c) 7-GHz optical filter bandwidths at the receiver.

indicates that the rejection of ASE noise is not the only reason of the performance improvement by using narrow bandwidth filtering for NRZ-duobinary. We used a computer simulation to visualize the underlying effect.

Fig. 3 shows the simulated eye diagrams of NRZ-duobinary with different filter bandwidths. There is a "narrow steep space valley" in the NRZ-duobinary eye diagram [as shown in Fig. 3(a)], which is the main factor that degrades the back-to-back performance of NRZ-duobinary. The narrow bandwidth optical filter can smooth and broaden the "narrow steep space valley." The eye diagram of the system with a 10-GHz bandwidth filter not only has a wider and smoother "space valley" than that with 20-GHz bandwidth filter, but has a lower "space level" as well. This factor together with the ASE noise rejection of the narrow bandwidth optical filter result in the 2-dB improvement of the back-to-back sensitivity. Further reducing the filter bandwidth induces significant signal loss and distortions, which will degrade the system performance, as shown in Fig. 3(c).

A. Dispersion Tolerance of NRZ-Duobinary With Narrow Bandwidth Optical Filtering

Fig. 4 shows the measured required OSNR at BER $= 10^{-3}$ versus chromatic dispersion for NRZ-duobinary when the optical filter bandwidths were about 11 and 71 GHz. It shows that the narrow bandwidth filtering not only improves the back-to-back sensitivity of the NRZ-duobinary system, but maintains the chromatic dispersion tolerance of NRZ-duobinary as well. Fig. 4 shows that for the amount of chromatic dispersion up to 2500 ps/nm, the required OSNR of the NRZ-duobinary with 11-GHz filter bandwidth is smaller than that with 71-GHz filter bandwidth, and for much larger chromatic dispersion, the narrow bandwidth filtering is a little bit worse than the wide bandwidth filtering. An interesting feature shown in Fig. 4 is that with the wide bandwidth optical filtering, the performance of NRZ-duobinary improves when the amount of chromatic dispersion is less than 2200 ps/nm. With the narrow bandwidth optical filtering, the required OSNR increases monotonically with chromatic dispersion, which again indicates that the back-to-back system was optimized.

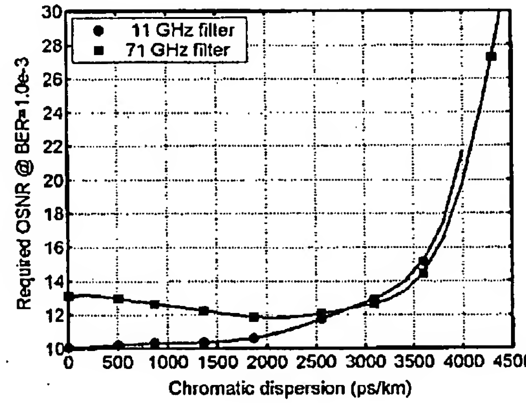

Fig. 4. Measured required OSNR at BER $= 10^{-3}$ versus chromatic dispersion for NRZ-duobinary with different optical filter bandwidths. Symbols are measured result and curves are polynomial fitting.

B. Dispersion Tolerance of RZ-Duobinary With Narrow Bandwidth Optical Filtering

Long-haul 40-Gb/s pseudolinear transmission systems are mainly limited by intrachannel nonlinear impairments. It has been shown that RZ is more tolerant to intrachannel nonlinearity than NRZ, and some additional phase modulation, such as RZ-DPSK and RZ-duobinary induces further improvement [11]. However, these RZ systems are more sensitive to residual chromatic dispersion. Here we propose to use a narrow bandwidth optical filter at the receiver in an RZ-duobinary system to increase its chromatic dispersion tolerance without sacrificing its good transmission performance.

The idea is to convert RZ-duobinary to NRZ-duobinary at the receiver side to increase its chromatic-dispersion tolerance. The narrow bandwidth optical filter (about one time bit rate) at the receiver together with the RZ-duobinary transmitter is equivalent to an NRZ-duobinary system. Before the narrow bandwidth optical filter, the signal is RZ-duobinary, and the good transmission performance of RZ-duobinary is maintained. After the narrow bandwidth optical filter, the signal is NRZ-duobinary, so the system can tolerate large residual chromatic dispersion. We demonstrated the key idea with a 10-Gb/s RZ-duobinary system. We also performed some simulations for 40-Gb/s systems, and found that the interaction of the residual dispersion and intrachannel nonlinearity had little effects on the system dispersion tolerance.

Fig. 5 shows the measured required OSNR at BER $= 10^{-3}$ versus chromatic dispersion for RZ-duobinary with 8- and 71-GHz optical filter bandwidths. This 8-GHz filter bandwidth was obtained by optimizing the optical filter bandwidth to get the smallest required OSNR at a chromatic dispersion of about

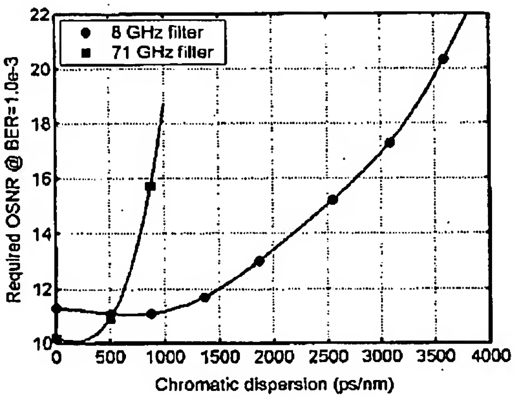

Fig. 5. Measured required OSNR at BER $= 10^{-3}$ versus chromatic dispersion for RZ-duobinary with different optical filter bandwidths. Symbols are measured result and curves are polynomial fitting.

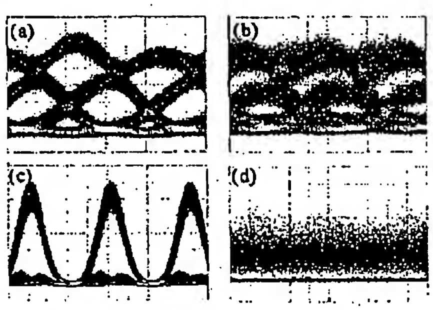

Fig. 6. Eye diagrams of RZ-duobinary with 8-GHz optical filter bandwidth at (a) back-to-back, (b) 3085-ps/nm chromatic dispersion, and (c) with 71-GHz optical filter bandwidth at back-to-back, (d) 3085-ps/nm chromatic dispersion.

3000 ps/km. For 2-dB OSNR penalty, the 10-Gb/s RZ-duobinary system with 71-GHz filter bandwidth can tolerate about ±600-ps/nm chromatic dispersion, while with 8-GHz filter bandwidth, it can tolerate about ±2000-ps/nm chromatic dispersion, about three times more than that with the wide filter bandwidth. Due to the larger loss of the signal power compared to the noise, there is about 1.5-dB sensitivity degradation for the back-to-back RZ-duobinary with 8-GHz filter bandwidth. Despite this, at the same OSNR level that corresponding to 2-dB penalty for the large filter bandwidth, the RZ-duobinary with the narrow filter bandwidth can still tolerate ±1500-ps/nm chromatic dispersion, about 2.5 times of that with the wide filter bandwidth. In addition, Fig. 5 indicates that by changing the bandwidth of the optical filter, we can adjust the receiver sensitivity and chromatic dispersion tolerance according to the requirements, which adds additional flexibility to the systems.

Fig. 6 shows the eye diagrams for the RZ-duobinary system with 8- and 71-GHz optical filter bandwidths at different amounts of chromatic dispersion. With the wide filter bandwidth, there is almost no signal information in the eye diagram when the system has about 3085-ps/nm chromatic dispersion. With 8-GHz filter bandwidth, the eye diagram of the back-to-back RZ-duobinary looks similar to that of NRZ-duobinary, and with even about 3085-ps/nm chromatic dispersion, the distortions of the eye diagram are moderate. As the RZ-duobinary was generated by using a pulse carver after the NRZ-duobinary transmitter, the pulses in "zeros" were not completely suppressed, so there were some ripples in "zeros," as shown in Fig. 6(c). Without these ripples, the system performance might be better for systems with both bandwidth filters.

III. Conclusion

We have shown that by using a narrow bandwidth optical filter at the receiver in a duobinary transmission system, its performance can be greatly improved. For NRZ-duobinary, the narrow bandwidth optical filter can significantly enhance the back-to-back sensitivity without sacrificing chromatic dispersion tolerance. For RZ-duobinary, it can greatly increase the chromatic dispersion tolerance of the system while still maintaining its good transmission performance.

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